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How can the UK road system be adapted to the impacts posed by climate change? By creating a climate adaptation framework

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ABSTRACT

This paper aims to analyse the impacts of climate change to the current and predicted future situations of road transportation in the UK and evaluate the corresponding adaptation plans to cope with them. A conceptual framework of long-term adaptation planning for climate change in road systems is proposed to ensure the resilience and sustainability of road transport systems under various climate risks such as flooding and increased temperature. To do so, an advanced Fuzzy Bayesian Reasoning (FBR) model is first employed to evaluate the climate risks in the UK road transport networks. This modelling approach can tackle the high uncertainty in risk data and thus facilitate the development of the climate adaptation framework and its application in the UK road sector. To examine the feasibility of this model, a nationwide survey is conducted among the stakeholders to analyse the climate risks, in terms of the timeframe of climate threats, the likelihood of occurrence, the severity of consequences, and infrastructure resilience. From the modelling perspective, this work brings novelty by expanding the risk attribute "the severity of consequence" into three sub-attributes including economic loss, damage to the environment, and injuries and/or loss of life. It advances the-state-of-the-art technique in the current relevant literature from a single to multiple tier climate risk modelling structure. Secondly, an Evidential Reasoning (ER) approach is used to prioritise the best adaptation measure(s) by considering both the risk analysis results from the FBR and the implementation costs simultaneously. The main new contributions of this part lie in the rich raw data collected from the real world to provide useful practical insights for achieving road resilience when facing increasing climate risk challenges. During this process, a qualitative analysis of several national reports regarding the impacts posed by climate change, risk assessment and adaptation measures in the UK road sector is conducted for the relevant decision data (i.e. risk and cost). It is also supplemented by an in-depth interview with a senior planner from Highways England. The findings provide road planners and decision makers with useful insights on identification and prioritisation of climate threats as well as selection of cost-effective climate adaptation measures to rationalise adaptation planning.

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1. Introduction

Climate change has been a frontier research topic involving diverse disciplines over the past decades. Current variability in climate poses a challenge for road infrastructure and operations. In many countries, road transport systems are sensitive to diverse weather extremes, including but are not limited to, variations in precipitation, temperature, winds, thunderstorms, frost, thaw and fog days, visibility and sea/water level (e.g., Love et al., 2010; Bles et al., 2010; Schweikert et al., 2014).

To adequately address the impacts of climate change on roads, adaptation strategies have been put forward and applied in real cases (e.g. Strauch et al., 2015). Although considerable research on climate adaptation has been undertaken in recent decades, existing studies focusing on climate adaptation of the transport sector are still scanty (e.g. Eisenack et al., 2012). A critical early step in establishing a comprehensive framework is to assess climate risks, including the types and levels, so as to strengthen the resilience and robustness of transport infrastructure and operations to these risks (Meyer et al., 2014).

Current research on climate-related risk analysis has commentators on interpreting and identifying the existing and future threats, estimating the level of risk as well as determining the level of uncertainties (Yang et al., 2015). However, traditional probabilistic risk analysis methods, such as Quantitative Risk Assessment (Nicolet-Monnier and Gheorghe, 1996; Urciuoli, 2011), are usually unable to deal with the unavailability or incompleteness of climate risk data. In the meantime, when the expressions of risk and costs are inconsistent, it is challenging to combine risk and cost results to make rational decisions (Yang et al., 2015). Some efforts have been put to address these challenges through combining fuzzy logic and Bayesian Networks (BNs) approaches to model subjective input data (Bott and Eisenhawer, 2002; Baksh et al., 2018), as well as combining fuzzy set modelling and evidential reasoning (ER) (e.g., Wan et al., 2018a) to realise climate risk and adaptation cost synthesis to minimise information loss (Wang et al., 1996). Furthermore, another research challenge is the uncertain nature of climate change itself, making it difficult to select and develop appropriate risk scenarios in which the analysis of diverse scenarios has been proven to enhance the resilience for unexpected changes (such as in a city (Mikovits et al., 2018)). Hence, a flexible climate adaptation framework is needed for addressing the above challenges and supporting road transport planners to make effective adaptation planning against climate risks in a specific region.

This work, based on the EU future city project (The Future Cities Adaptation Compass, 2012a, 2012b), proposes a conceptual framework for developing long-term climate change adaptation planning in transportation systems. It therefore offers a significant contribution to innovations in climate adaptation methods, in facilitating economic development and investment within the context of transportation planning. To achieve this, a hybrid of Fuzzy Bayesian Reasoning (FBR) and ER approaches is applied, to quantify the risks posed by climate change with the introduction of new risk parameters to better incorporate raw data for rational results. Furthermore, the developed FBR model is validated by the UK road transport system, through conducting a nationwide survey amongst 19 major road stakeholders. This application reveals the current and predicted future climate risks facing the road sector in the UK. Finally, by combining a review of the literature and national reports as well as an in-depth interview with a relevant road stakeholder, we disclose the existing and potential adaptation planning issues and provide useful recommendations for the UK road system. The outcomes of this paper can help fulfil the research need of road planners, decision-makers and industrial professionals on how to rationally design adaptation plans and implement adaptation measures and practices.

The remainder of this paper is structured as follows. A critical review of the impacts posed by climate change and climate risk analysis on roads is presented in Section 2. Section 3 introduces the methodology by elaborating a conceptual framework for developing long-term climate change adaptation planning in transportation systems with a step-by-step description. It includes an FBR model to evaluate the climate risks and adaptation measures in the transportation system and a nationwide survey for collecting first-hand data. A case study on how the British road system can adapt to the impacts of climate change is presented by following the above steps along with the supporting FRB and ER methods in Section 4. Finally, the discussion and research implications are presented in Section 5. The paper is concluded in Section 6 with suggestions for further research.

2. Critical review

Prior literature concerning the impacts on roads, posed by climate change, has developed both on a national or multi-regional level. In developed countries, such as the USA and the UK, a considerable number of studies have been carried out to investigate or assess the impacts of climate change on road sectors (e.g. Regmi and Hanaoka, 2011; Harvey et al., 2004; Galbraith et al., 2005; National Research Council of the National Academies (NRCNA), 2008; ICF International, 2008). These studies were not limited to the assessment and prediction of the impacts of climate change, but also the costs of mitigation and adaptation when corresponding measures are involved. However, most studies on climate change focused on short-term impacts. Furthermore, there are only few studies in the relevant literature dealing with road adaptation to climate change in developing countries (e.g. Koetse and Rietveld, 2009). Considering the complexity and diversity of climate change in different regions, it is necessary to undertake country-specific assessments and quantifications for climate change impacts and climate adaptation strategies to improve the resilience of a transport system. Meanwhile, proactive policy planning with an in-depth understanding of the projected climate change impacts on the built environment was suggested to avoid high costs in the future (Chinowsky et al., 2015).

The majority of current studies related to climate change adaptation primarily focused on physical infrastructures, such as bridges, pavements and drainage systems (TRB, 2008; De Bruin et al., 2009). Concerning climate adaptation of road infrastructure, Strauch et al. (2015) identified that the temperature changes in hydrological regimes increased flooding in autumn and reduced snowpack in spring, and higher soil moisture in winter led to the reduction of slope stability in Washington State, USA. Adaptation strategies were proposed to upgrade, change or maintain stream crossing and drainage design, revise funding policies, relocate or close roads and increase public participants. A methodological framework for developing adaptation strategies was developed

through exemplifying the management of rural roads in Thailand, where the vast road network was vulnerable to the impacts of flooding and sea level rise (SLR) (Rattanachot et al., 2015). De Bruin et al. (2009) put forward relatively holistic adaptation options for the Netherlands based on literature review and expert opinions. Overall, the most crucial adaptation strategies are, but not limited to, designing new vast infrastructure, improving the capacity of locks and weirs, developing more 'intelligent' infrastructure and water management systems. Some other specific adaptation measures include increasing the height of bridges and elevating road infrastructure in the case of water level rise, *etc.* (e.g., Demirel, 2011).

Despite all these pioneering attempts, the existing research on adapting transport to climate change is still scanty (i.e., Eisenack et al., 2012). Eisenack et al. (2012) and Koetse and Rietveld (2012) systematically reviewed the literature on climate adaptation strategies in the transport sector. Although the sector has realised its social and economic vulnerability to climate change, up to now, adaptation to climate change in transportation has received insufficient attention, especially on specific adaptation measures. Most studies tended to focus on a medium-size set of case studies rather than systematic strategies, and meanwhile, the context of the existing adaptation literature was either overly general, conceptual adaptations or site-specific technical measures (Eisenack et al., 2012; Koetse and Rietveld, 2012). Only a few countries have implemented specific adaptation strategies at a national level, such as the UK (DEFRA, 2006; Committee on Climate Change, 2014, 2017), the USA (EPA, 2009, 2014), the Netherlands (NAS, 2016) and Finland (Marttila et al., 2005; Ministry of Agriculture and Forestry, 2014). Through reviewing over 200 adaptations measures from 30 papers in 23 peer-reviewed journals from 2005 to 2009, Eisenack et al. (2012) found that the research was relatively scattered, lacking dominant journals, researchers and theories, and much knowledge on climate adaptation was not clarified in the peer-reviewed arena. The most institutional adaptations which could help planners make decisions were usually found in the grey literature.

To adapt to the impacts posed by climate change, a critical early step is to determine the types and levels of climate risks (Meyer et al., 2014). Many traditional risk assessment approaches have been extensively applied to perform risk assessment in different sectors. Nevertheless, in assessing the threat of landslides, for example, a limited number of studies have been undertaken to investigate the cost of damage or quantitatively analysed the effects of adaptation, which are probably because of the difficulties of collecting reliable data and of evaluating the effect of adaptation using an objective approach (Kim et al., 2018). Owing to the inadequacy of historical or statistical data on climate risks assessment, the high-level uncertainties in data (UNCTAD, 2012) make traditional probabilistic risk analysis methods, such as Quantitative Risk Assessment (Nicolet-Monnier and Gheorghe, 1996; Urciuoli, 2011) unsuited for climate adaptation study at this stage (Yang et al., 2018).

In recent years, fuzzy set and Bayesian Networks (BNs) methods have been applied to climate risk assessment on ports in several pioneering studies by a group of scholars. For instance, they exerted a 'discrete fuzzy set approach' and a 'fuzzy set manipulation' to accommodate subjective data in climate risk analysis (Ng et al., 2013; Yang et al., 2015, 2016, 2018). Through modelling subjective linguistic variables extracting from the stakeholders' opinions, climate risks were evaluated and projected based on their occurrence frequencies, the severity of consequences and timeframes of climate risks. In spite of showing much initial promise, these studies have yet attracted concerns from practice, including the difficulty of accurately evaluating the severity of consequence, and a lack of empirical evidence on the feasibility of the Fuzzy Bayesian modelling in adopting it from seaports to another transport context. More specifically, in previous studies (e.g., Yang et al., 2018), risk variables were defined in a high level at which experts in some cases felt insufficiently confident to carry out their evaluations. For instance, the consequences of climate change on many occasions need to be further interpreted from three perspectives including economic loss, human injuries/deaths, and environmental damage. Having them separately presented to model climate risk consequences will facilitate the use of raw data/subject judgements from experts and thus, provide a more rational and better climate risk evaluation mechanism. With reference to risk parameters, previous studies have mainly investigated the impacts of risky external events to infrastructure (e.g., the likelihood and severity of consequence) but not yet taken into account the resilience of the infrastructure itself. In the context of the transportation system, resilience was defined as the ability of the system to "absorb disturbances, maintain its basic structure and function, and recover to a required level of service within an acceptable time and costs after being affected by disruptions" (Wan et al., 2018a). Meanwhile, Wan et al. (2018b) also emphasised the necessity of incorporating the diverse characterises of transportation resilience into a new evaluation framework, together with advanced quantitative modelling methods to deal with uncertainties in resilience assessment. Hence, in this study, a new risk parameter namely "climate resilience" has been added to address this need. It can be interpreted as the capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a required period and cost of recovery (IPCC, 2012a).

Some recent articles have taken transport resilience into climate-related research. Beheshtian et al. (2018), for example, proposed a stochastic optimisation model for strengthening the long-term resilience of the motor fuel supply chain (MFSC) in response to the impacts of SLR and flooding in Manhattan, New York. The modelling results emphasised the importance of immediate risk management as well as investments of the vulnerable infrastructure at both early and late stages of the planning, retrofitting, and reconstruction for developing a successful climate adaptation framework. Nevertheless, it noted that previous Fuzzy Bayesian modelling studies have only been applied in the port area, while a systematic climate adaptation framework for the road system has not been created. Therefore, more empirical evidence is required in order to prove the model's feasibility in road transportation adaptation to climate change and enhance its generalisation.

One of the dilemmas remains is that the uncertain nature of climate change itself challenges the estimation and selection of risk (low-risk, medium-risk or high-risk) scenarios in the future. This issue can be addressed by collecting real survey data from transport experts to calibrate and assign the weights of the defined risk parameters so that the proposed model can be tailored and applied in different circumstances (Wu et al., 2013). This enlightens transport planners to consider diverse climate threats, and make a customised risk assessment and longer-term transport planning based on ongoing climate trend observations in a specific region. To do

so, it needs the input from continuous data collection and innovation of advanced models based on local conditions (Walker et al., 2011). Accordingly, a comprehensive climate risk analysis and adaptation framework is proposed below in response to the impacts of climate change.

3. Methodology

3.1. A conceptual framework of long-term adaptation planning for climate change

This new climate adaptation planning framework aims to systematically evaluate the climate risks on roads and select the cost-effective adaptation options in a situation where objective risk and cost data are incomplete or unavailable. It can be realised by utilising both quantitative and qualitative methods, for instance, an extended FBR model, practical surveys, and in-depth interview involving relevant road stakeholder. This section describes a four-step climate adaptation framework tailored from the EU future city project (The Future Cities Adaptation Compass, 2012a, 2012b), with novel supporting models in risk estimate and cost benefit analysis. It is followed by a real case to demonstrate how this framework is applied to climate risk assessment and adaptation planning in the British road sector in Section 4.

The Future Cities Adaptation Compass (2012a, 2012b) is an instruction tool for developing climate-proof city regions. Most of the sectors in a city (e.g., health, transportation, disaster and water management) confront the impacts posed by climate change. On the basis of this compass, this paper briefly describes a conceptual integrated climate adaptation framework specialised in the transportation systems, in which new subjective risk estimate and cost analysis models are proposed. It includes the following four steps:

Step 1: Identify climate risks on transportation systems.
Step 2: Evaluate the risks posed by climate change on transportation systems.
Step 3: Explore adaptation measures for transportation systems.
Step 4: Prioritise adaptation measures for transportation systems.

The above four steps are explained in the case study in Section 4. In Section 4.1, we identify climate risks on the UK roads referring to the UK Climate Projections (UKCP09) (Jenkins, 2009), the Highways England's latest report (2016) and other academic studies (i.e., Jaroszweski et al., 2010; Hooper and Chapman, 2012). These risks (and also adaptation options) are summarised in the questionnaire by a pilot study through interviewing domain experts. In Section 4.2, a national survey is carried out to collect data to evaluate climate risks confronting the UK road system using an advanced climate risk estimate approach described in Section 3.2. Section 4.3, addressing the above steps 3 and 4, describes the adaptation measures with respects to the high risks evaluated in Section 4.2. The reason for having the real data and case integrated with the methodology is twofold. One is the first two steps represent a standing alone technique for evaluating climate risks facing transport infrastructure. The other is the result of the case analysis in Section 4.2 can aid to explain the exploration and prioritisation of adaptation measures in Section 4.3 to provide useful insights in practice.

3.2. Evaluate the risks posed by climate change on transportation systems - a developed FBR risk analysis framework

In this section, the FBR risk analysis model for port adaptation to climate change (Yang et al., 2018) has been tailored to apply in the road sector, with new risk parameters and risk inference hierarchical structure. The following step-by-step description therefore mainly focuses on the new developments with new primary empirical information appropriately presented.[1]

<u>(1) Identify environmental drivers</u>

Based on the previous literature review (i.e., Jenkins, 2009; Jaroszweski et al., 2010; Hooper and Chapman, 2012), we summarise four primary environmental drivers affecting British roads due to climate change: (1) temperature increase, (2) intense rainfall/flooding, (3) more intense and/or frequent high winds and/or storms, and (4) SLR. Hence, this risk analysis is made with respect to each of these environmental drivers, to evaluate the risk level of their corresponding potential climate threats.

<u>(2) Identify climate risk variables</u>

The assessment of climate change risks on the road system may contain a variety of uncertainty and insufficient or incomplete historical data (UNCTAD, 2012). Hence, a fuzzy set method through modelling subjective linguistic variables can help tackle these issues (Yang et al., 2018).

First, eight climate risk parameters are newly identified and presented in a hierarchy structure of three levels respectively. On the first level is the top parameter called "Risk Level (RL)". It can be described by linguistic terms such as *"Very High", "High", "Medium", "Low" and "Very Low"* (e.g. Ng et al., 2013; Yang et al., 2015, 2016). On the second level, there are four parameters associated with climate risk evaluations. The linguistic terms used to describe the first three parameters *"Timeframe (T)", "Likelihood (L)" and "Severity of Consequences (C)"* in this level are consistent with those used in previous studies on port adaptation to climate change (e.g. Yang et al., 2008, 2009; Ng et al., 2013; Yang et al., 2016). All of the definitions of above parameters, sub-parameters as well as the descriptions of their linguistic terms are carefully examined by domain experts with reference to previous works in subjective risk modelling (Wang et al., 2018a, 2018b), and presented in Appendix A. For example, *"Timeframe"* means 'when does an expert expect

[1] It leaves the unnecessary repetitions in terms of modelling work (including equations and algorithms) to be explained in Yang et al. (2018).

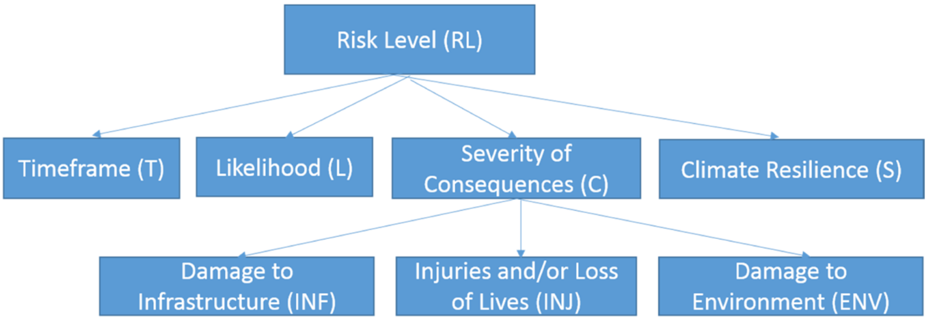

Fig. 1. Three-tier structure of climate risk parameters.

first to see this climate change impact'. Hence, the sooner he/she expect to see this impact, the higher risk level will be. Timeframe has been widely used to describe climate risks in previous studies (e.g. Yang et al., 2008, 2009; Ng et al., 2013; Yang et al., 2016). It has also been validated in the pilot study by the domain expert in the road transport sector. To reflect new climate adaptation studies, we add a new parameter "*Climate Resilience (S)*" in this study (IPCC, 2012a, 2012b), which is described as *"Very Weak", "Weak", "Average", "Strong"* and *"Very Strong"*. Because the traditional risk consequences are categorised into three groups including loss of life or injury, economic and environmental impacts and infrastructure damage (e.g., UNISDR, 2017), the *"Severity of Consequences (C)"* is divided into three sub-parameters: *"Damage to Infrastructure (INF)"*, *"Injuries and/or Loss of Lives (INJ)"*, and *"Damage to Environment (ENV)"*. Fig. 1 shows the three-tier structure of climate risk parameters.

Under fuzzy logic theory, the existing situational elements in risk analysis are each allocated a value or degree to which it belongs to a linguistic term - used to describe the risk parameters. We select triangular and trapezoidal membership functions in this paper given they are simple/accessible to a wide audience, and commonly used in risk analysis (i.e., Dyck et al., 2014). These functions based on the literature (e.g. Zhang et al., 2013; Yang et al., 2018) and domain experts' verification are expressed by five sets of overlapping triangular or trapezoidal curves, which are shown in Appendix A.

(3) Model the relation between low level and high level variables using fuzzy rule bases

IF-THEN rules collected from expert's knowledge are combined into a single system, by which the fuzzy system theory offers an efficient transformation from knowledge bases to non-linear mappings (Sii and Wang, 2002; Yang et al., 2010). To model the incomplete data from expert judgements, subjective degrees of belief (DoBs) are utilised and assigned to the linguistic terms to represent the uncertainty in data. For instance, a rule with DoB, describing the first and second level risk parameters, can be developed as follows:

- *If T is Very Short (VS), L is Very High (VH), C is Catastrophic (CA) and S is Average (A), then RL is Very High with a 75% DoB, Medium with a 25% DoB, Low with a 0% DoB and Very Low with a 0% DoB.*

The rationalisation of the DoB distribution of these rules is achieved by a proportion method (Alyami et al., 2014). Consequently, four second-level fuzzy input parameters including 20 (5 + 5 + 5 + 5) linguistic variables are assembled to generate 625 (5 × 5× ×5 × 5) antecedents with appropriate DoB distribution to the conclusions (i.e. the THEN part). Simultaneously, we construct a third-level network between the three parameters (INF, INJ and ENV) and the second-level parameter C, containing 15 (5 + 5 + 5) linguistic variables assembling to create 125 (5× ×5 × 5) antecedents, as shown in Appendix B.

(4) Prioritise risk levels by a BN technique

The employment of multiple sets of data makes it hard to use normal fuzzy rule inference mechanisms as the calculation causes loss of information and takes a long time. BN, as a sound mathematical method in minimising uncertainties and increasing knowledge, is able to integrate probability distributions or functions of various parameters and update their probabilities if new information emerges (Wang, 2003). It has been widely used in risk diagnosis and prediction in various areas, such as quantitative prediction and assessment of coastline change due to SLR (Gutierrez et al., 2011) and water-related health issues triggered by extreme weather events (Bertone et al., 2015). In this paper, we utilise BN to facilitate the synthesis of fuzzy rules and to evaluate climate risks in a semi-automation manner.

Taking the rule base of the first and second level as an example, we convert the constructed structure into a five-node converging connection, where the rule base is expressed by conditional probabilities. This connection contains four parent nodes, N*T*, N*L*, N*C* and N*s* (Nodes *T, L, C*, and *S*) and one child node N*RL* (Node *RL*).

In the questionnaire survey, we ask participants to estimate the impacts of climate change on their road networks regarding *"Timeframe", "Likelihood", "Severity of Consequence"* and *"Climate Resilience"* with reference to their individual linguistic terms, so as to obtain the prior probabilities of all four nodes. The prior probabilities of N*L*, *p(L)*, for example, can be obtained by asking the question, "how likely the effect will occur when you expect first to see this climate threat poses impacts on the road that your organisation is associated with?". We then averaged all the data received from different experts. For the multiple data from one group, we first average the data within the group to minimise the input of obvious subjective bias.

Finally, the marginal probability of risk level N*RL* can be computed based on the given prior probabilities (Jensen, 2001). After

the allocation of utility values to the linguistic terms (i.e. risk levels) of N*RL*, the final climate risk ranking value by multiplying the obtained marginal probabilities and the associated utility value of the risk levels. The lower the climate risk ranking value, the higher the risk level is.[2]

3.3. A nationwide survey for assessing climate risks and exploring adaptation options

To test the feasibility of the extended FBR model, a large-scale survey was conducted to collect primary data through examining the perceptions of road stakeholders on the impacts of climate change, and effects of adaptation for climate change. This survey aims to illustrate the general situation of climate risks in the UK road system and further justify the necessity of adaptation planning. It included the evaluation of overall impacts and specific threats on the operations, performance, and infrastructure of British roads. The questions were categorised into two types: closed-ended and open-ended. In particular, participants were asked to describe the risk level of each specific risk threat with and without adaptation measures by the linguistic terms concerning its timeframe, severity of consequence, likelihood and climate resilience. In addition, we required the information of financial costs of each adaptation measure for further cost-effectiveness assessment. To guarantee the validity of this questionnaire, a pilot study was undertaken in April 2017 by speaking with eight professional road experts and academics in the UK. The 12 potential climate threats on the road and their corresponding adaptation measures were then finalised (see Tables 1 and 3) by combining the literature review (i.e., UNECE, 2012; Regmi and Hanaoka, 2011) and the results from the domain experts' survey.

From May to December 2017, we assessed the perception of 19 road experts on climate change risks through a nationwide online survey. The survey participants widely ranged from CEOs/transport directors, transport planners, transport engineers, environmental managers, private operators, transport authorities, highway agencies and NGOs to road academics. A summary listed the background information of domain experts can be found in Appendix C. Transport entities in charge of the "M" (i.e. motorway) and "A" class roads in the UK were targeted as primary participants in this survey.

Given the uniqueness and complexity of climate change issues (i.e., the characteristics, geographic distribution, scales and types of climate risks on roads), non-probability sampling, including a combination method of judgment and snowball sampling, was utilised (Wang, 2015). Some small entities in remote regions were excluded as they might lack necessary knowledge or experience of climate change issues, and meanwhile, the representativeness of the samples is more critical than its generalisability in judgment sampling (Vogt and Gardner, 2012). Combining the above factors, there were two criteria for the survey sampling: (1) members of The UK Roads Liaison Group (UKRLG); (2) Other main road entities that can provide the geographical balance of each region in the UK. Consequently, a sample of 30 administrators representing the essential transport institutions of different regions in the UK (e.g., Highways England, Transport for Greater Manchester, AECOM UK, *etc.*) was selected to assess their perceptions of climate change risks. Afterwards, we invited one or two critical informants at each entity from the targeted population to help distribute our questionnaire by a snowballing method.

We distributed the 30 questionnaires through BOS Online Survey (BOS, 2017). E-mails and phone calls were used to contact all the respondents. In the end, 19 out of 30 valid responses were received with a high response rate of 63.3%.

3.4. Use of ER for cost-effectiveness analysis of adaptation measures

Finally, the ER approach is used to evaluate the cost-effectiveness of the explored adaptation measures against the climate threats of high risks at the last step of this methodology. For instance, risk reduction with adaptations cost of the *nth* adaptation measure for tackling the *mth* climate threat can be synthesised to obtain the cost-effectiveness of the *nth* adaptation measure against the threat.

The whole process of ER calculations to obtain the final results of the combined DoB β^j ($j = 1, 2, 3, 4, 5$) can refer to the latest algorithm pathway.[3]

Furthermore, utilising centroid defuzzification method (Mizumoto, 1995; Yang et al., 2009), the linguistic description can then be converted into crisp values {0.11, 0.3, 0.5, 0.7, 0.89} (Yang et al., 2018) so as to obtain a numerical cost-effectiveness index (*CEI*) of each adaptation measure.

4. Case study: risks analysis and climate change adaptation framework on the UK road system

4.1. Identify climate risks on the UK road system

Based on the UK Climate Projections (UKCP09) (Jenkins, 2009), the Highways England's latest report (2016) and other academic studies (i.e., Jaroszweski et al., 2010; Hooper and Chapman, 2012), we firstly identify the predicted climate change trends and impacts on the British road transport. These include the effects of an increased number of hotter and drier days in summer and warmer and wetter days in winter, increased heavy precipitation and extreme weather events, drought, sea level change, seasonal change, high winds, and reduced number of fog days and cloud cover. For example, higher temperatures in summer can cause road

[2] The risk result from the fuzzy Bayesian model was presented by grade assessment with belief degrees. To obtain a crisp value to prioritise the climate threats, we assigned each assessment grade a utility value and then calculated the final risk score by the addition of multiplying the belief degree associated with a specific grade and the grade's utility value.

[3] The detailed algorithm has been explained in previous studies (e.g., Yang et al., 2018).

Table 1
Questionnaire results of climate risk analysis on UK roads.
Sources: CEDR (2012); IPCC (2012b); Regmi & Hanaoka (2011); The Royal Academy of Engineering (2011); UNECE (2012).

Environmental driver due to climate change	Potential climate threat on the road	Risk ranking value	Ranking of risk level
Temperature increase	A1. Increased intensity of warm weather leads to pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt	0.54	9
	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	0.51	8
	A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	0.40	1
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	0.43	2
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	0.44	3
	B3. Rainfall events result in landslides and mudslides in hilling roads, and cause roadblocks	0.47	4
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	0.48	5
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	0.50	7
	C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign	0.51	8
	C3. High wind and storms can increase traffic accidents and affect road safety	0.48	5
SLR	D1. SLR can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	0.49	6
	D2. SLR can deteriorate road base and bridge supports, cause bridge scour and pollution under bridges	0.50	7

damage; more intense precipitation in winter might result in flooding, landslips, and bridge scour. An interviewee from Highways England also added a few main impacts on its road network. He suggested that the changing precipitation (groundwater level/flooding/storm surges) might lead to pollution and asset deterioration, and affect the design and management of existing foundations, drainage and skid resistance. Increase in extreme temperature could alter the layout of bearings and expansion joints. High winds may have minor effects on structure and gantries but major risks of disruption of construction work.

During this process, all the four critical climate threats (i.e., temperature increase, intense rainfall/flooding, more intense and/or frequent high winds and/or storms, and SLR) as well as their corresponding adaptation measures are identified and examined by eight road experts via a preliminary study, and finally listed in the questionnaire survey for further evaluation.

Historically, strong winds are considered to be the most dangerous weather type for the UK roadways (Perry, 1990; Edwards, 1994). The UK is one of the windiest countries located in the mid-latitude westerlies. A destructive wind event 'Windy Thursday', occurred on 18 January 2007 fiercely swept over major regions of England, Scotland and Wales (Eden, 2007). This event resulted in the overturning of approximately 50 goods vehicles and £50 million losses of delay across the nation (Highways Agency, 2007). The following significant wind storms over this period resulted in 111 accidents and lengthy recovery time after the disruption (Eden, 2007). Additionally, high winds, due to the occurrence of the latest Storm Ali in September 2018, led to power cuts, vehicle damages and fallen trees which further caused traffic disruptions in Cumbria, including the closure of partial sections of M6 and the Tay Road Bridge (BBC News, 2018).

With the sea level rises, 5% of the UK major road network was expected to suffer from 'significant' annual change of coastal flooding (Edwards, 2017). Flooding also presented significant impact on climate change on the UK transport networks and around 10% of the UK major road networks was built in floodplains, and 7% had a 'significant to moderate' chance of annual flooding (EPA, 2009). This can be witnessed from the cumulative effect of the rapid succession of 12 significant storms from December 2013 to February 2014 in the UK since the 1950s (Met Office, 2014; Devon Maritime Forum, 2014). They contributed to the collapse of 80 sections of the sea wall at Dawlish on the South Devon coast, backlog in carriageways, increased number of potholes, severe road deterioration and thousands of fallen trees and branches on the roads, as well as multi-sectional road closures (e.g., A30, A38, A30 and A303) (Devon County Council, 2014).

The most catastrophic floods occurred in Cumbria UK 2015, partly as a result of Storm Desmond occurred on the 5th and 6th December, which broke 2009's precipitation record with 341.4 mm rainfalls (Met Office, 2015). Roads were shut in the severely affected areas, and over 100 bridges were damaged or destroyed. The A595 was closed from the Castle Roundabout at Cockermouth to the Thursby roundabout near Carlisle (BBC News, 2015). With the flooding of A595, the main road was damaged and requires to be rebuilt. The broken traffic lights also caused temporary delays in the both ways of A590 at Lindal (The Mail, 2015).

Overall, although some recent studies have begun to cope with climate impacts (i.e., Peterson et al., 2008; Koetse and Rietveld, 2009), the existing research on climate impact on road freight in the UK has remained relatively unexplored (Jaroszweski, 2015). The

lack of precise data on the current and potential impacts of climate change, as well as cost-benefit analysis, poses a significant challenge for transportation planners, which could potentially cause the failure of adaptation strategies in the transport sector (i.e., Koetse and Rietveld, 2012). Hence, we propose an extended climate risk analysis framework by utilising the FBR approach and collecting primary data through a nationwide survey to reveal the real climate risks in British roads.

The UK highway industry began developing a holistic asset management plan for climate change in 2010 (Munslow, 2011). 'Climate Change Adaptation Framework' (Highways Agency, 2009) and the recently published 'Climate Adaptation Risk Assessment Progress Update' (Highways England, 2016) described the existing climate risk assessment approaches and adaptation procedures. The current climate risk appraisal considers *the rate of climate change, the extent of disruption, the severity of disruption* and *uncertainties*,[4] based on the methodology used in the project of 'Risk Management for Roads in a Changing Climate (RIMARPCC)' (Conference of European Directors of Roads, 2010). Nevertheless, this method becomes arguable when not taking other critical factors influencing climate impact into account, such as the costs, time and capacity of a transport system to recover from the risks of a climate change event. Furthermore, the forthcoming UKCP18 projections may change the level of climate risks, which requires reviewing the existing action plans and discussing the derived products and budgets, instead of merely prioritising risks by formula. Department for Environment, Food & Rural Affairs (DEFRA) has been looking at a more standardised approach for climate risk assessment. Hence, it is vital to fill the gaps in analysing the cost-effectiveness of adaptation measures and constructing adaption plans for climate change in the UK road network.

4.2. Evaluate climate risks for the UK road system by using FBR model

First of all, the climate risks of each potential climate threat of environmental driver related to UK roads with no adaptation measures being implemented are calculated by the above fuzzy Bayesian approach and the results are elaborated in Table 1. The evaluations of each threat are depended upon the four aforementioned risk parameters: *"Timeframe (T)", "Likelihood (L)", "Severity of Consequence (C)" and "Climate Resilience (S)".*

Utilising FBR and its associated Hugin software (HUGIN v. 8.5, 2017; Andersen et al., 1989), the risk results of "A1. Extended warm weather can cause pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt", for example, can be calculated as {2.38% Very high, 20.78% High, 35.21% Average, 36.15% Low, 5.48% Very low}. After assigning the utility values to the five linguistic terms, A1's risk index value is calculated as 0.54. The result of risk analysis on A1 by Hugin is found in Fig. 2.

Based on the ranking results in Table 1, the highest climate risks to the roads in Britain are "A3", "B1" and "B2", which refers to "A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs owing to increased temperature", "B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions", and "B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts", respectively. The threat of the lowest risk level is "(A1) Extended warm weather can cause pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt because of increased temperature". This is probably due to the fact that the influence of increased temperature on road pavement is a long process where substantial economic losses may not be visualised in a short time.

To figure out the different opinions from diverse groups regarding climate risks on roads, this survey investigates the participants' positions and types of their companies or organisations. After that, these data are analysed against three different criteria: (1) Engineers (including transport engineers, bridge design leads and freight and logistics technologists); CEOs (including CEO/transport directors, development/strategy directors, traffic & local road associate directors and policy makers); managers (including transport planners, environmental managers, heads of highways, waste & property, and advanced solution managers), as well as an academic staff (a road research fellow) by their positions; (2) consulting companies, NGOs, transport companies and academia, by the type of their entities; (3) large, middle and small companies or organisations by the scale of their entities. Utilising the above FBR method, the results of risk levels, including the utility value and ranking of each potential climate threat are calculated (Appendix D).

With regards to the participants' position (Table D1), the climate threat "A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs" posed by "temperature increase" is the top concern given that three out the four groups of stakeholders evaluate it with the lowest utility values as academics (0.37), managers (0.4) and engineers (0.4). It indicates that they (i.e. academia, managers and engineers) expect sooner, stronger, more likely and weaker resilient climate risks on their associated roads compared to the group of CEOs (0.41) regarding "A3". This is possibly because engineers and managers tend to involve in the day-to-day road operations and evidence the damages to the road infrastructure that they use or are in charge of due to climate change. In particular, compared with other groups, academics hold the highest risk views on the impacts of temperature increase (i.e., "A3") but also the lowest ones on the intense rainfall/flooding, and more intense and/or frequent high winds and/or storms (i.e., "B3", "B4" and "C2"). This indicates that the academic's climate risk perception is quite different with industrialists, triggering new research to better understand the driver behind the difference. It, therefor, raises the research urgency in the field where industrial concerns/needs are higher than academic expectations and possible reactions.

In terms of the type of participants' entity (Table D2), NGOs, academia and consulting companies expect the highest-level climate

[4] For instance, when prioritisation criteria is highly disruptive, time-critical with high confidence, "Indicator score = [Rate of climate change] × [Extent of disruption] × [Severity of disruption] × (4 − [Uncertainty]) divided by 81" (Conference of European Directors of Roads, 2010).

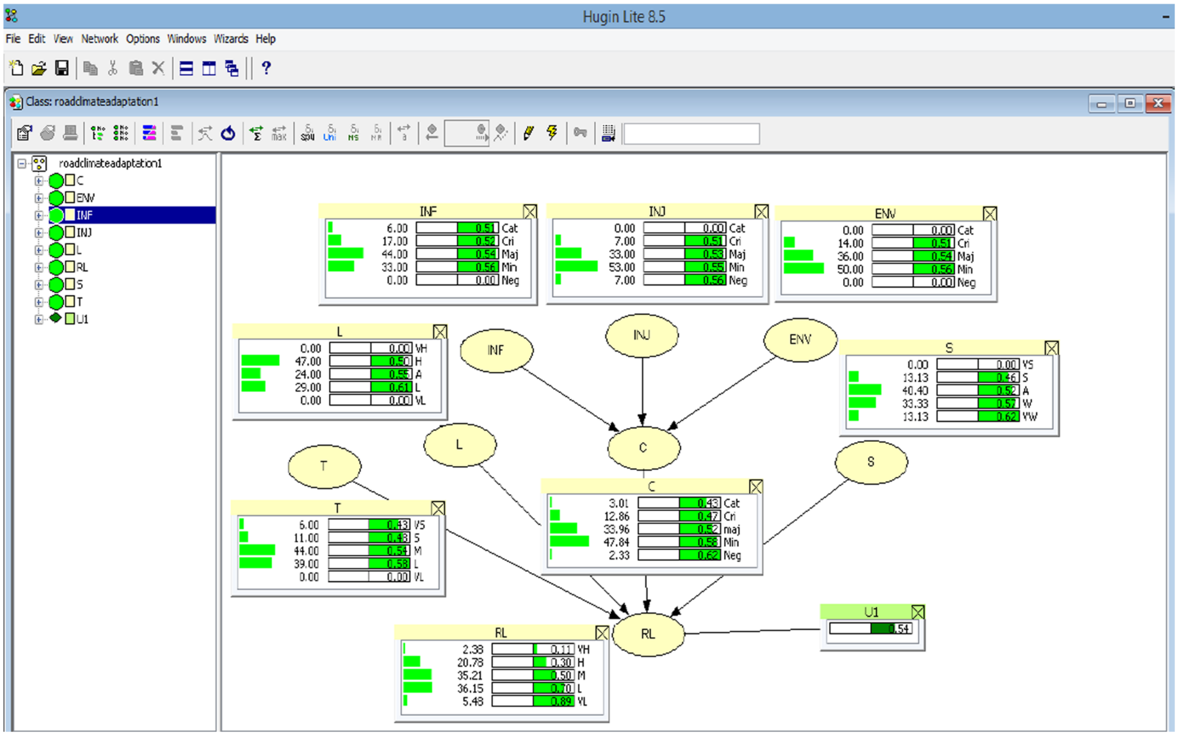

Fig. 2. Climate risk analysis of “A1. Extended warm weather can cause pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt” using Hugin.

risks regarding “A3”, as well as “B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions” owing to “intense rainfall/flooding”. NGOs and consulting companies have lots of engagements with a variety of projects and stakeholders in the road network; they have a higher chance to provide comprehensive views on climate impact on roads. Similarly, the analysis results show that academia has the lowest risk-level evaluation on “B3”, “B4” and “C2”. Again, it reveals variations in understanding the risks posed by climate change between academics and practitioners.

Finally, concerning the scale of participants’ entity (Table D3), we divide them into three categories: large (more than 50,000 employees), middle (1000–50,000 employees) and small (less than 1000 employees) entities. Large and middle entities estimate a highest-level risk scenario for “A3” owing to “temperature increase”. By contrast, small and middle entities consider the lowest risks posed by more intense and/or frequent high wind and/or storms and SLR (A1, B4 and C2). It could because the larger-scale companies/organisations are more likely to be exposed to the impacts of climate change as their operations usually involve larger or more complicated road networks, thus having more concerns on this topic.

By averaging the utility values of each category and corresponding group, the overall ranking of risk levels of the investigated

Table 2
Questionnaire results of climate risk analysis on UK roads with respect to the different groups.

Category		Average values of all risk level	Overall Ranking of Risk Level
Position	Engineer	0.49	3
	CEO	0.47	2
	Manager	0.45	1
	Academic	0.54	4
Type	Consulting	0.48	2
	NGO	0.46	1
	Transport Company	0.49	3
	Academia	0.54	4
Scale	Large	0.47	1
	Middle	0.50	3
	Small	0.48	2

climate threats can be found in Table 2. It is notable that managers from large NGOs hold the highest risk-level views. Meanwhile, according to the above categorisation analyses, the climate threat "A3" is always the top concern. Thereafter, "B4" and C2" receive the least attention from both academics and middle companies/organisations (i.e. "B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable" due to "intense rainfall/ flooding" and "C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign" because of "more intense and/or frequent high wind and/or storms").

4.3. Explore and prioritise adaptation measures for the UK road system

In response to the impacts of climate change on transportation infrastructure, the UK government has recognised adaptations on infrastructure as a need of high priority. For example, an early report called "Climate Resilient Infrastructure: Preparing for a Changing Climate" was published together with guidance on building infrastructure resilience in 2011 (HMG, 2011; HM Cabinet Office, 2011). The "Transport Resilience Review" introduced by the Department of Transport (2014) provided Highways England with detailed recommendations for adapting to extreme weather. Highways England's Climate Adaptation Risk Assessment (2016) highlighted a series of current adaptation action plans, mainly focusing on road structures, pavements and drainage management, and will continuously monitor all the potential climate vulnerabilities. Several regional flooding adaptation actions, including the design and constructions of flood defences to protect the people and properties, have been undertaken in severely jeopardised regions. A good example of risk management was the success of dealing with the Cockermouth's flooding in 2009. The government allocated approximately £1 million funding to support the clean-up and repairs of damaged roads and bridges within Cumbria. Additionally, Network Rail and Cumbrian County Council implemented a modal shift strategy by converting road traffic to the rail by quickly setting up a new direct rail service (DRS) and building a rail platform in Workington (Ace Geography, n.d.).

Nevertheless, according to the Adaptation Sub-Committee's Progress Report (Committee on Climate Change, 2014), current action plans are still at the stage of internal technical documents within the relevant business areas; a detailed action plan for climate adaptation has not been officially published. Adaptation strategies are necessary to be incorporated into the planning stages of new developments as well as existing maintenance to minimise risks, reduce costs and enhance the resilience of the UK transport network in the future (Jaroszweski, 2015). Hence, it is vital to fill the gaps in analysing the cost-effectiveness of adaptation measures and constructing adaption plans for climate change in the UK road network.

In this section, we apply an ER approach to synthesise the risk reduction results obtained by the above mentioned fuzzy Bayesian method and the associated adaptation costs data from a questionnaire survey to select the most cost-effective adaptation measures.

In our questionnaire, we asked the experts to evaluate each climate threat with and without the adaptation measures, in terms of the aforementioned risk parameters *("Timeframe (T)", "Likelihood (L)", "Severity of Consequences (C)" and Climate Resilience (S)")*. In the case of having the adaptation measures, we also required them to evaluate the costs of implementation of adaptation measures.

The risk reductions can be calculated by the described FBR model while the corresponding adaptation costs were collected through survey and expert opinions. The parameter *"Cost-Effectiveness of Adaptation Measure"* is defined by five levels, namely, *"Very Effective", "Effective", "Average", "Slightly Effective"* and *"Ineffective"* while *"Adaptations Cost"* is defined by *"Very low", "Low", "Average", "High"* and *"Very High"* by the same membership functions as other risk parameters (Yang et al., 2015, 2018). When adaptation measures involve, the risk reduction of the *mth* climate threat by implementing *nth* adaptation measure is calculated by the difference between the risk index of the *mth* climate risk with the *nth* adaptation measure and the risk index of the *mth* climate risk index without any measure.

We then utilise the Hugin software to simplify the calculations to obtain all the risk levels with and without the adaptation measures. For instance, the evaluations of the potential threat "A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces" due to the "Temperature increase" without and with the adaptation measure "(A2a) Prioritise the selection of material, manage expansion joints and decay protection (i.e., use of revised specification with material characteristics more suited to higher temperatures and temperature profiles)" is changed from 0.51 to 0.53, and therefore, the risk reduction result is 0.02. Likewise, the risk results of all potential threats of the environmental driver on the UK roads are elaborated in Table 3, in which the adaptation measures receiving no significant risk reduction are eliminated.

In order to transform both climate risk and cost data into the same level, the risk reduction grades are mapped onto the five-level cost-effectiveness, where maximal risk reduction grade is interpreted as to be *"Very Effective"* and minimal risk reduction grade means *"Ineffective"* adaptation measures. The other in-between risk reduction values are allocated using a linear distribution. Simultaneously, adaptation costs are firstly obtained by averaging the survey responses and then converted into the five-level cost-effectiveness, where *"Very low"* cost is taken as to be *"Very Efficient"* adaptation measure and *"Very High"* cost means *"Ineffective"* measure. Furthermore, the ER approach (Yang and Xu, 2002) allows us to integrate the results of risk reduction with adaptations cost of the *nth* adaptation measure for tackling the *mth* climate threat to obtain its cost-effectiveness. The final cost- effectiveness analysis results of all adaptation measures are shown in Table 4.

The most cost-effective adaptation measure is "(B2b) Strengthen the foundation of bridges, river and bank protection, and corrosion protection" to address the potential threat "B2. Rainfall events can cause rivers/watercourses to flood which damages bridges,

Table 3
Survey results of risk reduction and adaptation costs.
Sources: CEDR (2012); IPCC (2012b); Regmi & Hanaoka (2011); The Royal Academy of Engineering (2011); UNECE (2012).

Environmental driver due to climate change	Potential climate threat on the road	Adaptation measures	Risk Result without adaptations	Risk result with adaptations	Risk reduction RR_{mn}	Risk reduction grades {VE, E, A, SE, I}	Cost {VH, H, A, L, VL}
Temperature increase	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	(A2a) Prioritise the selection of material, manage expansion joints and decay protection (i.e., Use of revised specification with material characteristics more suited to higher temperatures and temperature profiles)	0.51	0.56	0.05	{0, 0, 0.6667, 0.3333, 0}	{0.10, 0.30, 0.40, 0.20, 0}
		(A2b) Design and construct new bridges or replace old ones (i.e., Designs which support the revised specifications in B1 – so that supporting materials have revised specification for performance in line with B1)	0.51	0.53	0.02	{0, 0, 0, 0.6667, 0.3333}	{0.09, 0.36, 0.45, 0.09, 0}
	A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays, and consequential costs	(A3a) Map the highway network and infrastructure asset base and identify at-risk locations/structures where there are issues as measured under different scenarios	0.40	0.50	0.10	{0.3333, 0.6667, 0, 0, 0}	{0, 0.18, 0.09, 0.55, 0.18}
		(A3b) Provision of timely driver information to 'at risk' routes	0.40	0.52	0.12	{1, 0, 0, 0, 0}	{0, 0.09, 0.09, 0.45, 0.36}
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	(B1a) Consider drain specifications to handle different rain conditions	0.43	0.50	0.07	{0, 0.3333, 0.6667, 0, 0}	{0, 0.38, 0.31, 0.31, 0}
		(B1b) Consider revised standards for drainage sewers (not the actual drain itself) to support the drain in A1	0.43	0.55	0.12	{1, 0, 0, 0, 0}	{0, 0.33, 0.33, 0.33, 0}
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	(B2a) Improve flood estimation	0.44	0.49	0.05	{0, 0, 0.6667, 0.3333, 0}	{0.08, 0.08, 0.67, 0.08, 0.08}
		(B2b) Strengthen the foundation of bridges, river and bank protection, and corrosion protection	0.44	0.55	0.11	{0.6667, 0.3333, 0, 0, 0}	{0.18, 0.36, 0.45, 0, 0}
	B3. Rainfall events result in landslides and mudslides in hilling roads, and cause roadblocks	(B3a) Consider Slope, drain performance in landslide scenarios	0.47	0.57	0.10	{0.3333, 0.6667, 0, 0, 0}	{0.08, 0.08, 0.50, 0.33, 0}
		(B3b) Design standards for highways which performance to revised standards with different rain events	0.47	0.51	0.04	{0, 0, 0.3333, 0.6667, 0}	{0, 0.15, 0.38, 0.31, 0.15}
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	(B4a) Map the highway network and infrastructure asset base and identify at-risk locations/structures where there are issues as measured under different scenarios	0.48	0.50	0.02	{0, 0, 0, 0.6667, 0.3333}	{0.08, 0.08, 0.17, 0.50, 0.17}
		(B4b) Provision of timely driver information to 'at risk' routes	0.48	0.50	0.02	{0, 0, 0, 0.6667, 0.3333}	{0, 0.25, 0.17, 0.25, 0.33}

(*continued on next page*)

Table 3 (*continued*)

Environmental driver due to climate change	Potential climate threat on the road	Adaptation measures	Risk Result without adaptations	Risk result with adaptations	Risk reduction RR_{mn}	Risk reduction grades {VE, E, A, SE, I}	Cost {VH, H, A, L, VL}
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	(C1b) Consider revised height standards for highways based on scenario modelling in the area	0.50	0.56	0.06	{0, 0, 1, 0, 0}	{0, 0.18, 0.36, 0.36, 0.09}
	C2. Damage to lighting fixtures and supports, traffic boards and information sign	(C2a) Resilience in signs and use of nonphysical means such as telematics in vehicle and sensor technology	0.51	0.48	0.03	{0, 0, 0, 1, 0}	{0, 0.18, 0.27, 0.45, 0.09}
	C3. Disrupt traffic safety and emergency evacuation operations, increase traffic accidents	(C3a) Map the highway network and infrastructure asset base	0.48	0.51	0.03	{0, 0, 0, 1, 0}	{0, 0.08, 0.25, 0.50, 0.17}
		(C3b) Identify at risk locations/structures where there are issues as measured under different scenarios	0.48	0.51	0.03	{0, 0, 0, 1, 0}	{0, 0.08, 0.46, 0.31, 0.15}
		(C3c) Provision of timely driver information to 'at risk' routes	0.48	0.50	0.02	{0, 0, 0, 0.6667, 0.3333}	{0, 0.10, 0.30, 0.40, 0.20}
SLR	D1. SLR can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	(D1a) Revised standards to meet/cope with higher sea levels (i.e. greater time of immersion in water)	0.49	0.55	0.06	{0, 0, 1, 0, 0}	{0, 0.10, 0.10, 0.80, 0}
		(D1b) Revised standards of signage and edge standards, and resilience in signs and use of nonphysical means such as telematics in vehicle and sensor technology to higher areas, and edge strengthening	0.49	0.51	0.03	{0, 0, 0, 1, 0}	{0, 0.10, 0.30, 0.50, 0.10}
	D2. SLR can deteriorate erosion of road base and bridge supports, cause bridge scour and pollution under bridges	(D2a) Revised standards for scour risk caused by higher sea levels	0.50	0.47	0.03	{0, 0, 0, 1, 0}	{0.11, 0.11, 0.22, 0.33, 0.22}
		(D2b) Map bridge structures for the impact of higher levels as to operating performance under normal and extreme scenarios	0.50	0.51	0.01	{0, 0, 0, 0.3333, 0.6667}	{0, 0.30, 0.30, 0.30, 0.10}

Table 4
Cost-effectiveness of adaptation measures and ranking.

Environmental driver due to climate change	Potential climate threat on the road	Adaptation measures	Cost-effectiveness index of adaptations	Cost effectiveness ranking
Temperature increase	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	(A2a) Prioritise the selection of material, manage expansion joints and decay protection (i.e., Use of revised specification with material characteristics more suited to higher temperatures and temperature profiles)	0.5090	8
		(A2b) Design and construct new bridges or replace old ones (i.e. Designs which support the revised specifications in B1 – so that supporting materials have revised specification for performance in line with B1)	0.5912	12
	A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	(A3a) Map the highway network and infrastructure asset base and identify at-risk locations/structures where there are issues as measured under different scenarios	0.4325	5
		(A3b) Provision of timely driver information to 'at risk' routes	0.4097	4
Intense rainfall/flooding	B1. The road drainage cannot efficiently remove water due to heavy rains, which results in poor or dangerous driving conditions	(B1a) Consider drain specifications to handle different rain conditions	0.4546	6
		(B1b) Consider revised standards for drainage sewers (not the actual drain itself) to support the drain in B1a	0.3040	2
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	(B2a) Improve flood estimation	0.5293	9
		(B2b) Strengthen the foundation of bridges, river and bank protection, and corrosion protection	0.2587	1
	B3. Rainfall events result in landslides and mudslides in hilling roads, and cause roadblocks	(B3a) Consider Slope, drain performance in landslide scenarios	0.3717	3
		(B3b) Design standards for highways which performance to revised standards with different rain events	0.5057	7
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	(B4a) Map the highway network and infrastructure asset base and identify at-risk locations/structures where there are issues as measured under different scenarios	0.6972	19
		(B4b) Provision of timely driver information to 'at risk' routes	0.7057	20
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	(C1b) Consider revised height standards for highways based on scenario modelling in the area	0.5300	10
	C2. Damage to lighting fixtures and supports, traffic boards and information sign	(C2a) Resilience in signs and use of nonphysical means such as telematics in vehicle and sensor technology	0.6549	14
	C3. Disrupt traffic safety and emergency evacuation operations, increase traffic accidents	(C3a) Map the highway network and infrastructure asset base	0.6801	17
		(C3b) Identify at-risk locations/structures where there are issues as measured under different scenarios	0.6587	15
		(C3c) Provision of timely driver information to 'at risk' routes	0.7060	21
SLR	D1. SLR can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	(D1a) Revised standards to meet/cope with higher sea levels (i.e. greater time of immersion in water)	0.5667	11
		(D1b) Revised standards of signage and edge standards, and resilience in signs and use of nonphysical means such as telematics in vehicle and sensor technology to higher areas, and edge strengthening	0.6676	16
	D2. SLR can deteriorate erosion of road base and bridge supports, cause bridge scour and pollution under bridges	(D2a) Revised standards for scour risk caused by higher sea levels	0.6517	13
		(D2b) Map bridge structures for the impact of higher levels as to operating performance under normal and extreme scenarios	0.69	18

culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts”. The other top two adaptation measures “(B1b) Consider revised standards for drainage sewers (not the actual drain itself) to support the drain in B1a” and “(B3a) Consider Slope, drain performance in landslide scenarios” are also aimed to address “intense rainfall/flooding” issues. Whilst the least effective one is “(C3c) Provision of timely driver information to ‘at risk’ routes” to cope with the potential threat “C3. Disrupt traffic safety and emergency evacuation operations, increase traffic accidents” due to the “more intense and/or frequent high wind and/or storms”.

5. Discussion and research implications

The findings from the survey of 19 experts in this study offer a board overview of how roads can be adapted to climate change impacts in the UK. Overall, temperature increase, precipitation change/flooding and extreme weather are considered as the top three environmental drivers due to climate change followed by snow, flooding and high wind.

Unsurprisingly, the modelling results show that the highest potential climate threats to the roads in Britain fall into “A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs owing to increased temperature”, followed by “B1”. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions”, and “B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts”, respectively. Interestingly, among the top concerned risks owing to increased temperature, the impacts including traffic jams, alternative routing, accidents and delivery delays are highly related to the public’s daily life. While increasing fuel consumption, CO_2 emissions and consequential costs are also visible and widespread issues which have been discussed in past decades. These findings are also consistent with the current priorities of tackling flooding and increased temperature issues in climate change adaptation in the UK, but they are more specific so as to provide insights for the further development of practical adaptation measures. For instance, the most cost-effective adaptation measures in most categorisation are associated with to tackling the most significant threats “B1” and “B2” due to “intense rainfall and flooding”. In other words, some measures can been successfully adapt to the threats of intense rainfall and flooding on the UK roads, thereafter, another high risk related to temperature increase (i.e. “A3”) has not yet been well addressed with cost-effective measure. It reveals the fact that more resources are still required for dealing with diverse climate change threats by effective adaptation planning.

The perceptions from 19 domain experts, such as CEOs/transport directors, transport planners, transport engineers and road academics, stand in the overall situation with regard to the impacts of climate change and adaptations in the UK roads. By dividing participants into three categories in terms of their position, and type and scale of their entities, managers from large NGOs hold the most concerns on climate risks and their impacts on the UK road system. Simultaneously, the threat “A3” is on the top list among all the groups. By contrast, “B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable” posed by “intense rainfall/flooding” and “C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign” posed by “more intense and/or frequent high wind and/or storms” are the lowest risky threats from the perspectives of academia and middle-size entities.

Notably, almost all the respondents who provide the details about their experience on climate impacts in the past ten years stress flooding. For example, significant floods caused widespread damage to highway infrastructure, road deterioration and closures, service stoppage, as well as bridges being washed away in June 2000, November 2006, June 2012, July 2014 and December 2015. Similarly, our modelling results indicate that the most cost-effective adaptation measures are all relevant to the risks posed by intense rainfall/flooding, namely “(B2b) Strengthen the foundation of bridges, river and bank protection, and corrosion protection”, “(B1b) Consider revised standards for drainage sewers (not the actual drain itself) to support the drain in B1a” and “(B3a) Consider Slope, drain performance in landslide scenarios”. Therefore, it can be interpreted that there are two cost-effective measures, “(B1b)” and “(B2b)” to address the top risk threats “(B1)” and “(B2)” respectively regarding the flooding issue on roads. Our society has more experience and mature measures (of less uncertain knowledge) on tackling flooding, compared to other climate risks. However, for temperature increase, the current adaptation measures, such as “(A3a)” and “(A3b)”, are still insufficient to tackle the significant climate risk “(A3)”.

Although existing adaptation plans for climate change were recognised to be at an initial stage, 28% of total respondents have implemented an adaptation plan, and 33% have shown a positive intention to make a specific adaptation plan for climate change impacts in the future. As for the adaptation planning horizon, Highways England is required to report every five years under the Adaptation Reporting Power in the Climate Change Act, which is also in line with the official climate projects (last used UKCP09). Current time horizon of road asset life/activity is evaluated by two general categories: short-term ($<$ 30 years) and longer-term ($\geq$30 years). Whilst the time horizon for climate change effects can be divided into short-term (present-2020), mid-long term (2020–2080) and long-term (beyond 2080) (Highways England (2016)). Owing to the uncertainties of climate change itself, adaptation plans should consider a longer time horizon for addressing climate change issues in the future. This time horizon could be linked to asset lifecycles up to 120 years, as an interviewee stated. In the meantime, the project-based characteristic in road planning may diversify the time horizon in different road routes depending upon complex conditions (i.e., geography, severity and likelihood

of climate change, and adaptation budgets). Accordingly, to set up a reasonable time horizon for adaptation planning, it requires considering multiple factors including road asset lifecycle, climate projects and route characteristics, *etc.*, to be explored more in future.

From the answers to the open-ended questions, we find that one of the significant challenges in future planning is to guarantee that climate change is embedded in standards, which needs a review of technical specifications (e.g., the Design Manual for Roads and Bridges) (Highways England (2016)). With a new set of climate projections (UKCP18) published in Nov 2018 by the UK government, more review and discussion around derived products in the road sector are remained to be done. The demands of adapting transport to climate change and extreme weather, including both transport policy and infrastructure development, have been re-emphasised in recent discussions of the International Transport Forum (ITF, 2015a, 2015b, 2016). Other mitigation measures, at the meantime, should be combined with adaptation measures to combat carbon emission, as one of the top concerns due to increased temperature revealed by our survey and a primary objective highlighted in Highways England Delivery Plan (2015–2020) (Highways England, 2015). Moreover, risk analysis is still on top of the list for future adaptation planning and might necessitate a standardised approach established by diverse stakeholders (i.e., in UKCP18 Government User Group). Last but not least, a successful adaptation plan is made on the basis of informing budgetary constraints and striking a balance between technical opinions and corporate priorities.

6. Conclusions

In summary, this paper presents an innovative conceptual framework of adaptation planning for climate change and how it fits the UK road network. The study performs a comprehensive risk analysis, through applying a mathematical FRB model to quantify the climate risks posed by climate change and prioritise the cost-effective adaptation measures when objective data is unavailable or incomplete in reality. The utilisation of mix-methods including literature review, survey and interview not only offers primary data for modelling requirements but also lays an essential foundation to trigger a broader discussion about adaptation planning in road systems.

Both theoretical and practical contributions are achieved. In light of the previous climate adaptation research on ports, this paper reiterates the reliability and validity of the utilisation of FBR model in the context of transport systems. From the modelling perspective, this work brings novelty by considering climate resilience and expanding the risk attribute of severity of consequence into three sub-attributes including economic loss, damage to the environment, and injuries and/or loss of life. It advances the-state-of-the-art techniques in the current relevant literature from a single to multiple tier structure. The main contributions in this part lie in the rich raw data collected from real world that provides useful practical insights for road resilience when facing increasingly frequent and severe climate change events.

Furthermore, being a pioneer survey on the British road network with latest primary data offers a comprehensive overview of the most significant risks posed by climate change and corresponding cost-effectiveness adaptation measures. The survey results have supported the evidence for the existence of a number of the relevant issues identified in the literature review (e.g., temperature increase and flooding). With the increasing number of studies on climate risks management on diverse transportation systems, it is anticipated, therefore, the findings of this paper will contribute to future regional studies and trigger more in-depth discussions in relevant topics, especially for the multi-mode research (such as in seaports and airports (Poo et al., 2018; Monioudi et al., 2018).

This paper also has its practical implications for the road industry. The useful adaptation framework for constructing or developing an adaptation plan for climate change offers a new thinking pattern by integrating mathematical modelling and qualitative consultation into decision making. Besides, the results are expected to be shared with most of the participants in the survey including highway authorities, transport consulting companies, governments and relevant associations. Thus, it calls for more attention of transport administrators on the significance of the impacts that climate change poses to road planning. Through illustrating a general situation of climate change and adaptation planning on the UK road sector, the survey results also provide transport stakeholders with a better interpretation on the existing climate risks.

However, it is admitted that the single consultation with Highways England may not be convincing, hence, future works might continuously refine the proposed framework via case studies (e.g., more interviews) with relevant bodies, such as Environmental Agency, Transport for London and other local transport authorities. This adaptation framework together with risk analysis methods are of high generalisation and can be tailored and used to climate change adaptation effectively, such as in different transport modes (i.e., risk assessment in railways (Wang et al., 2018) and multiple regions (i.e., developing countries) to further strengthen its flexibility and advantages. These ideas will open further research questions and build upon existing knowledge, approach and data collection.

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Appendix A. Definition of parameters

See Tables A1 and A2.
See Tables A3.1–A3.3.
See Table A4.

The climate resilience can be influenced by three factors. The worst-case scenario is applied to assess the system's resilience for simplifying the description to allow experts choose linguistic terms. For instance, if the capacity of the transport system to recover is "Very Strong", the time of the recovery is "Strong" and the cost of recovery is "Weak", then the final assessment result should be "Weak".

Table A1
Timeframe - when you expect first to see this impact.

Grade	Linguistic terms	Approximate timeframe	Fuzzy memberships
1	Very Short (VS)	< 1 year	(0, 0, 0.1, 0.3)
2	Short (S)	1–5 years	(0.1, 0.3, 0.5)
3	Medium (M)	5–15 years	(0.3, 0.5, 0.7)
4	Long (L)	15–20 years	(0.5, 0.7, 0.9)
5	Very Long (VL)	> 20 years	(0.7, 0.9, 1, 1)

Table A2
Likelihood that the effect will occur.

Grade	Linguistic terms	Likelihood	Fuzzy memberships
1	Very High (VH)	> 90%	(0, 0, 0.1, 0.3)
2	High (H)	60–90%	(0.1, 0.3, 0.5)
3	Average (A)	40–59%	(0.3, 0.5, 0.7)
4	Low (L)	10–39%	(0.5, 0.7, 0.9)
5	Very Low (VL)	< 10%	(0.7, 0.9, 1, 1)

Table A3.1
Severity of consequences of this impact:—damage to infrastructure (INF).

Grade	Linguistic terms	The damage committed to property is valued	Fuzzy memberships
1	Catastrophic (CA)	> £2million	(0, 0, 0.1, 0.3)
2	Critical (CR)	£1million - £2million	(0.1, 0.3, 0.5)
3	Major (Ma)	£500,000 - £999,999	(0.3, 0.5, 0.7)
4	Minor (MI)	£100,000 - £499,999	(0.5, 0.7, 0.9)
5	Negligible (NE)	< £100,000	(0.7, 0.9, 1, 1)

Table A3.2
Severity of consequences of this impact:—injuries and/or loss of lives (INJ).

Grade	Linguistic terms	Injuries and/or loss of life	Fuzzy memberships
1	Catastrophic (CA)	Life-threatening injuries or loss of life	(0, 0, 0.1, 0.3)
2	Critical (CR)	Major injuries and lost time incident	(0.1, 0.3, 0.5)
3	Major (Ma)	Injuries and lost time incident	(0.3, 0.5, 0.7)
4	Minor (MI)	Minor injuries, no lost time incidents	(0.5, 0.7, 0.9)
5	Negligible (NE)	No injuries, no lost time incidents	(0.7, 0.9, 1, 1)

Table A3.3
Severity of consequences of this impact:—damage to environment (ENV).

Grade	Linguistic terms	The percentage of this event contributes to the total amount of damage of surrounding environment	Fuzzy memberships
1	Catastrophic (CA)	> 50%	(0, 0, 0.1, 0.3)
2	Critical (CR)	30–50%	(0.1, 0.3, 0.5)
3	Major (Ma)	20–29%	(0.3, 0.5, 0.7)
4	Minor (MI)	10–19%	(0.5, 0.7, 0.9)
5	Negligible (NE)	< 10%	(0.7, 0.9, 1, 1)

Table A4
Climate resilience.
Source: IPCC (2012a).

Grade	Linguistic terms	Description	Fuzzy memberships
1	Very Weak (VW)	Very weak (0–20%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a very long period (a year) and very high cost of recovery (£10million above)	(0, 0.1, 0.3)
2	Weak (W)	Weak (20–39%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a long period (a month) and high cost of recovery (£1million above)	(0.1, 0.3, 0.5)
3	Average (A)	Average (40–59%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event and requiring a certain length of time (a week) and cost of recovery (£100,001–£1 million)	(0.3, 0.5, 0.7)
4	Strong (S)	Strong (60–80%) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a relatively timely and efficient manner (a day) and requiring some cost of recovery (£10,001–£100,000)	(0.5, 0.7, 0.9)
5	Very Strong (VS)	Very strong (80% above) capacity of the transportation system to anticipate, absorb, accommodate, or recover from the effects of a climate event in a very timely and efficient manner (12hrs) and requiring a slight cost of recovery (0-£10,000)	(0.7, 0.9, 1, 1)

Appendix B. FRB with belief structures for climate risk analysis

Rules	Antecedent attributes				Risk Level (RL)				
	Timeframe (*T*)	Likelihood (*L*)	Severity of consequence (*C*)	Climate resilience (*S*)	Very high	High	Medium	Low	Very low
1	Very Short (VS)	Very High (VH)	Catastrophic (CA)	Very Weak (WV)	100%	0	0	0	0
2	VS	VH	CA	Weak (W)	75%	25%	0	0	0
3	VS	VH	CA	Average (A)	72%	0	25%	0	0
…	…	…	…	…	…	…		…	…
623	Very Long (VL)	Very Low (VL)	Negligible (NE)	A	0	0	25%	0	75%
624	Very Long (VL)	Very Low (VL)	Negligible (NE)	Weak (W)	0	0	0	25%	75%
625	Very Long (VL)	Very Low (VL)	Negligible (NE)	Very Strong (VS)	0	0	0	0	100%

Appendix C. The background information of transport experts in the pilot study

Expert 1: Transport planner, AECOM UK
Expert 2: Policy maker, Leeds City Council
Expert 3: Transport planner, South Tyneside Council
Expert 4: Academic, University of Westminster
Expert 5: Head of highways, Ynys Mon Country Council
Expert 6: Transport engineers, North & Mid Wales Trunk Road Agent
Expert 7: Senior manager, Transport for Greater Manchester
Expert 8: Team leader, transport System Catapult.

Appendix D. Questionnaire results

See Tables D1–D3.

Table D1
Questionnaire results of climate risk analysis on UK roads by position.

Environmental driver due to climate change	Potential climate threat on the road	Position	Utility value	Ranking of risk level
Temperature increase	A1. Increased intensity of warm weather leads to pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt	Engineer	0.56	17
		CEO	0.44	5
		Manager	0.53	14
		Academic	0.53	14
	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	Engineer	0.56	17
		CEO	0.54	15
		Manager	0.49	10
		Academic	0.50	11
	A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	Engineer	0.40	2
		CEO	0.41	3
		Manager	0.40	2
		Academic	0.37	1
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	Engineer	0.44	5
		CEO	0.44	5
		Manager	0.41	3
		Academic	0.43	4
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	Engineer	0.45	6
		CEO	0.48	9
		Manager	0.41	3
		Academic	0.48	9
	B3. Rainfall events result in landslides and mudslides in hilling roads, and cause roadblocks	Engineer	0.48	9
		CEO	0.45	6
		Manager	0.40	2
		Academic	0.63	20
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	Engineer	0.46	7
		CEO	0.43	4
		Manager	0.48	9
		Academic	0.66	22
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	Engineer	0.49	10
		CEO	0.47	8
		Manager	0.45	6
		Academic	0.56	17
	C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign	Engineer	0.47	8
		CEO	0.46	7
		Manager	0.51	12
		Academic	0.65	21
	C3. High wind and storms can increase traffic accidents and affect road safety	Engineer	0.51	12
		CEO	0.49	10
		Manager	0.46	7
		Academic	0.50	11
SLR	D1. SLR can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	Engineer	0.52	13
		CEO	0.51	12
		Manager	0.45	6
		Academic	0.60	18
	D2. SLR can deteriorate erosion of road base and bridge supports, cause bridge scour and pollution under bridges	Engineer	0.52	13
		CEO	0.55	16
		Manager	0.48	9
		Academic	0.61	19

Table D2
Questionnaire results of climate risk analysis on UK railways by type of entity.

Environmental driver due to climate change	Potential climate threat on the road	Type	Utility value	Ranking of risk level
Temperature increase	A1. Increased intensity of warm weather leads to pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt	Consulting	0.59	18
		NGO	0.42	5
		Transport Company	0.51	14
		Academia	0.55	16
	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	Consulting	0.50	13
		NGO	0.44	7
		Transport Company	0.52	15
		Academia	0.50	13
	A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	Consulting	0.39	2
		NGO	0.40	3
		Transport Company	0.52	15
		Academia	0.37	1
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	Consulting	0.46	9
		NGO	0.37	1
		Transport Company	0.42	5
		Academia	0.43	6
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	Consulting	0.46	9
		NGO	0.43	6
		Transport Company	0.43	6
		Academia	0.48	11
	B3. Rainfall events result in landslides and mudslides in hilling roads, and cause roadblocks	Consulting	0.45	8
		NGO	0.46	9
		Transport Company	0.41	4
		Academia	0.63	20
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	Consulting	0.47	10
		NGO	0.47	10
		Transport Company	0.48	11
		Academia	0.68	22
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	Consulting	0.50	13
		NGO	0.51	14
		Transport Company	0.49	12
		Academia	0.57	17
	C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign	Consulting	0.47	10
		NGO	0.50	13
		Transport Company	0.55	16
		Academia	0.65	21
	C3. High wind and storms can increase traffic accidents and affect road safety	Consulting	0.46	9
		NGO	0.51	14
		Transport Company	0.52	15
		Academia	0.50	13
SLR	D1. SLR can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	Consulting	0.46	9
		NGO	0.50	13
		Transport Company	0.46	9
		Academia	0.60	19
	D2. SLR can deteriorate erosion of road base and bridge supports, cause bridge scour, and pollution under bridges	Consulting	0.52	15
		NGO	0.45	8
		Transport Company	0.52	15
		Academia	0.60	19

Table D3
Questionnaire results of climate risk analysis on UK railways by the scale of the entity.

Environmental driver due to climate change	Potential climate threat on the railway	Scale	Utility value	Ranking of risk level
Temperature increase	A1. Increased intensity of warm weather leads to pavement deterioration, including softening, traffic-related rutting, cracking, migration of liquid asphalt	Large	0.53	13
		Middle	0.51	11
		Small	0.56	16
	A2. Heating and thermal expansion of bridges, buckling of joints of steel structure and paved surfaces	Large	0.46	6
		Middle	0.50	10
		Small	0.45	5
	A3. Traffic jams/alternative routing/accidents, increasing fuel consumption and CO_2 emissions, delivery delays and consequential costs	Large	0.39	2
		Middle	0.37	1
		Small	0.54	14
Intense rainfall/flooding	B1. The road drainage cannot effectively remove water due to heavy rains, which results in poor or dangerous driving conditions	Large	0.45	5
		Middle	0.43	3
		Small	0.43	3
	B2. Rainfall events can cause rivers/watercourses to flood which damages bridges, culverts waterways and clearance, and scouring can ruin the foundation of bridges and culverts	Large	0.45	5
		Middle	0.43	3
		Small	0.46	6
	B3. Rainfall events result in landslides and mudslides in hilling roads, and cause roadblocks	Large	0.47	7
		Middle	0.54	14
		Small	0.44	4
	B4. The road may be inundated by flooding caused by adjacent drainage systems (rivers/public sewers) flooding which renders the road unusable	Large	0.45	5
		Middle	0.58	17
		Small	0.43	3
More intense and/or frequent high wind and/or storms	C1. Storm cyclone due to heavy rainfall and high wind can trigger flooding, inundation of embankments, affect road transport and stability of bridge decks	Large	0.47	7
		Middle	0.51	11
		Small	0.49	9
	C2. Disrupt traffic safety and emergency evacuation operations, damage to lighting fixtures and supports, traffic boards and information sign	Large	0.48	8
		Middle	0.58	17
		Small	0.50	10
	C3. High wind and storms can increase traffic accidents and affect road safety	Large	0.47	7
		Middle	0.53	13
		Small	0.53	13
SLR	D1. SLR can trigger inundation of coastal roads, extra demands on infrastructure when used as emergency/evacuation roads, and realign or abandon roads in threatened areas	Large	0.49	9
		Middle	0.49	9
		Small	0.48	8
	D2. SLR can deteriorate erosion of road base and bridge supports, cause bridge scour and pollution under bridges	Large	0.52	12
		Middle	0.55	15
		Small	0.46	6

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